

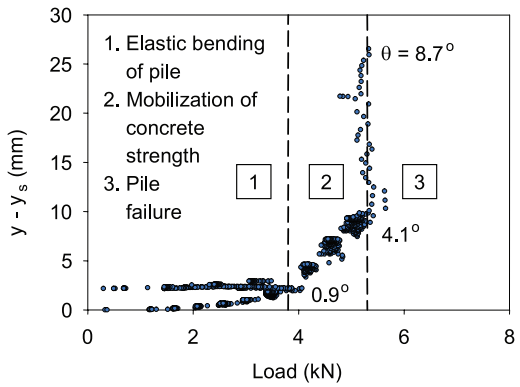
Implementation Benefits

The research findings are expected to benefit civil and geotechnical engineers of government transportation agencies, consultants, and contractors dealing with slope stability, slope remediation, and geotechnical testing in Iowa. In situ BST measurements provide reliable, site-specific soil parameters for design applications, which can lead to substantial cost savings over using empirical estimations for critical soil properties. Because the BST is an alternative to expensive and time-consuming laboratory testing, the device is particularly useful in obtaining relatively large amounts of data necessary for probabilistic analyses. The BST is primarily intended to test cohesive soils.

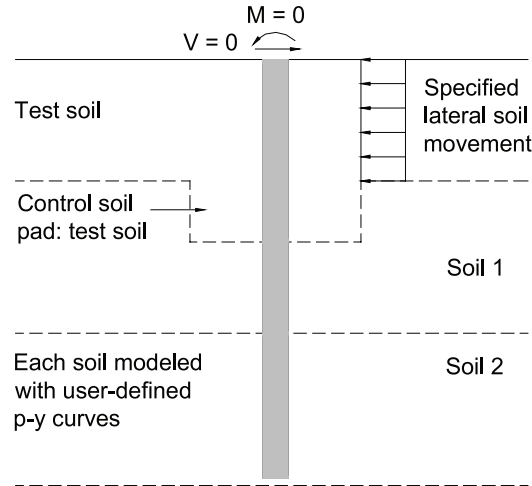
Implementation Readiness

The research demonstrates with experimental testing how lateral forces develop along stabilizing piles to resist slope movements. The research report documents a step-by-step procedure that can be used by both state and county transportation agencies to design slope reinforcement using slender piles. While slope reinforcement with slender piles by county transportation agencies is encouraged, such action is recommended to be coordinated with the state department of transportation. This organization can document all such remediation projects to better guide counties using successful and unsuccessful experiences, as the DOT will have working knowledge of other unstable slope characteristics and corresponding reinforcement designs.

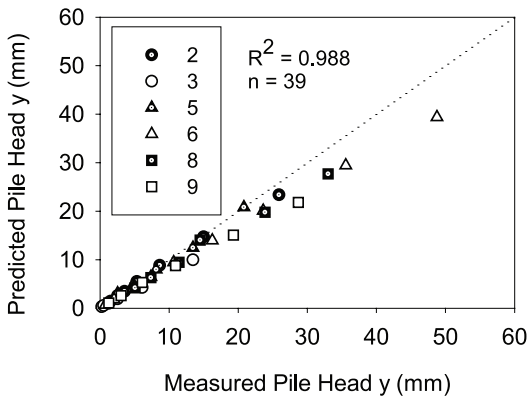
The proposed slope reinforcement solution has not yet been demonstrated at an Iowa slope failure site. As a result, difficulty in scheduling and bidding a pile reinforcement project and evaluating the effectiveness of the measure may impede successful implementation. Obtaining experience and feedback through data collection or visual inspection, however, will promote incorporation of the research findings into standard slope remediation practice.



Behavioral stages of piles subject to lateral soil movement



LPILE model for analyzing load test results



Pile head deflection correlation for isolated piles to pile section failure



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**RESEARCH PROJECT TITLE**  
Innovative Solutions for Slope Stability Reinforcement and Characterization (TR-489)

**SPONSORS**  
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Iowa Department of Transportation

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The Partnership for Geotechnical Advancement (PGA) is part of the Center for Transportation Research and Education (CTRE) at Iowa State University. The mission of the PGA is to increase highway performance in a cost-effective manner by developing and implementing methods, materials, and technologies to solve highway construction problems in a continuing and sustainable manner.

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Innovative Solutions for Slope Stability Reinforcement and Characterization

tech transfer summary

This research aims to improve slope stability investigations and analysis through use of the in situ Borehole Shear Test and to establish the use of micropile reinforcement as a viable slope remediation.

Objectives

- Develop and validate procedures for determining in situ shear strength parameters using the Borehole Shear Test (BST).
- Classify and characterize weathered shale materials associated with slope instability.
- Demonstrate the importance and effectiveness of using a relatively large amount of in situ shear strength data for slope stability analyses using probabilistic methods.
- Interpret the load distributions induced on pile elements by lateral soil movements.
- Characterize the structural behavior of slender pile subject to lateral soil movement.
- Develop design procedures for slope reinforcement using slender pile elements.

Problem Statement

Failures of slopes occur throughout the world and contribute to economic and casualty losses. These losses, intuitively proportional to the magnitude of failure, are direct and indirect costs to individuals and institutions. The impact of slope failures on these losses is often undervalued. Every year, the United States experiences more than \$1 billion in damages and approximately 50 deaths; worldwide, slope failures cause hundreds of billions of dollars in damage and hundreds of thousands of deaths. More locally, the annual cost for remediation and maintenance of slopes often exceeds state and county transportation budgets. Current understanding of such socioeconomic losses justifies the allocation of funds needed for slope stability research.

Slope Stability Characterization

Characterization of slope failures is complicated because the factors affecting slope stability can be difficult to discern and measure, particularly soil shear strength parameters. Extensive research has been conducted on slope stability investigations and analysis. The current research, however, focused on applying an infrequently-used testing technique comprised of the Borehole Shear Test (BST). This in situ test rapidly provides effective (i.e., drained) shear strength parameter values of soil. Using the BST device, 15 Iowa slopes (14 failures and one proposed slope) were investigated and documented.

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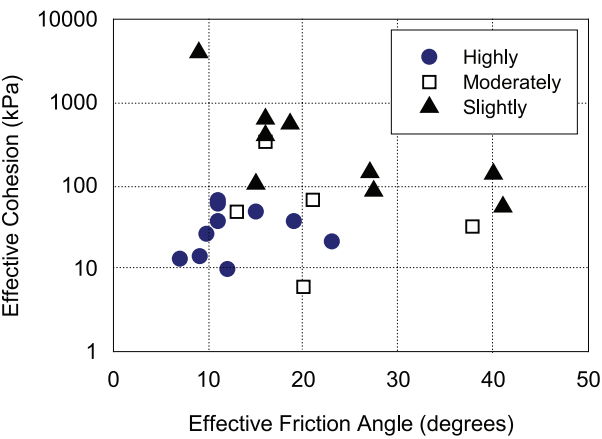


*Slope Stability Characterization continued*

Particular attention was paid to highly-weathered shale and glacial till soil deposits, which have both been associated with slope failures in the southern Iowa drift region. Conventional laboratory tests, including direct shear tests, triaxial compression tests, and ring shear tests, were also performed on undisturbed and reconstituted soil samples to supplement BST results. The shear strength measurements were incorporated into complete evaluations of slope stability using both limit equilibrium and probabilistic analyses.

**Slope Reinforcement**

Remediation of slope failures requires stabilization alternatives that address causes of slope instability. Slope reinforcement using pile elements can be an effective method of remediation in preventing slope movements in weak soils where enhanced drainage does not provide adequate stability. Soil load transfer to pile elements from the downslope soil movement, as occurs in slope failures, is a complex soil–structure interaction problem. Soil–structure interactions for small-diameter, grouted pile elements subject to lateral soil movement were investigated by conducting full-scale pile load tests, in which piles installed through a shear box into stable soil were loaded by uniform lateral translation of soil. Instrumentation of the shear boxes and pile reinforcement indicated the load distributions that developed along the piles. The load test analyses support the claim that the distributed loads, which are mobilized during pile loading, depend on the relative displacement between the soil and pile elements. The reliable estimation of these load distributions is important because the influence of piles on the global stability of the slope depends directly on the pile loading condition.



*BST results for weathered shale soils*



*Iowa BST performance using hollow-stem auger as borehole casing*



*Iowa BST device: shear head*



*Iowa BST shear plates after shearing: normal shear plates (left) and high stress shear plates (right)*



*High-slump grout placement during pile installation for load tests*



*Large-scale direct shear test setup*

**Key Findings**

**Slope Characterization**

- The Borehole Shear Test measures peak shear strength parameters outside the failure zone and “softened” parameters inside the failure zone.
- Backcalculated shear strengths for slope failures (FS = 1.0) were generally higher than residual shear strengths from ring shear tests on reconstituted samples and lower than peak shear strengths from in situ Borehole Shear Tests.
- Probabilistic slope stability analyses are useful when a relatively large amount of data is available, such as shear strength parameters from BSTs. The probability of slope instability is evaluated based on the statistical distribution of the soil shear strengths and the groundwater surface.

**Slope Reinforcement**

- The installation of slender piles in weak soils offers considerable resistance to lateral soil movement, with improvement factors ranging from 1.2 to 6.6.
- Pile section moment capacities were mobilized, indicating that a “flexible” pile failure mode was achieved.
- The insertion of pile elements into strain-softening weathered shale and glacial till soils altered the soil behavior, negating the strain softening aspects of the unreinforced soils.
- The relative soil–pile displacement at the soil surface indicates the behavioral stages of small-diameter piles as (1) mobilization of soil shear stresses and elastic pile bending, (2) mobilization of pile concrete compressive strength, and (3) incipient failure due to mobilization of pile moment capacity.
- The behavioral characteristics of slender piles are controlled by structural pile behavior through moment–curvature relationships as much as they are by soil behavior.
- Displacement-based lateral response analysis methods, which use soil p-y curves, accurately predict the deflection and bending moment of piles subject to lateral soil movement. From these pile behavior characteristics, pile shear may be calculated and applied to the limit equilibrium equation for evaluating global stability of reinforced slopes.

